Polarization in lamp-post model of black-hole accretion discs

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Abstract: We re-visit the lamp-post geometry of the black-hole accretion disc with a primary illuminating source on the rotational axis. The primary power-law radiation is Compton reflected from the disc towards the observer. The gravitational field of a rotating black hole influences the photon properties on its way from the primary source to the disc and from the primary source and accretion disc to a distant observer. We study the polarization properties of the radiation how they would be observed in this scenario. The degree and the angle of polarization are examined as functions of the black hole spin, observer's inclination angle, height of the primary source and total intensity received at infinity.

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The model components

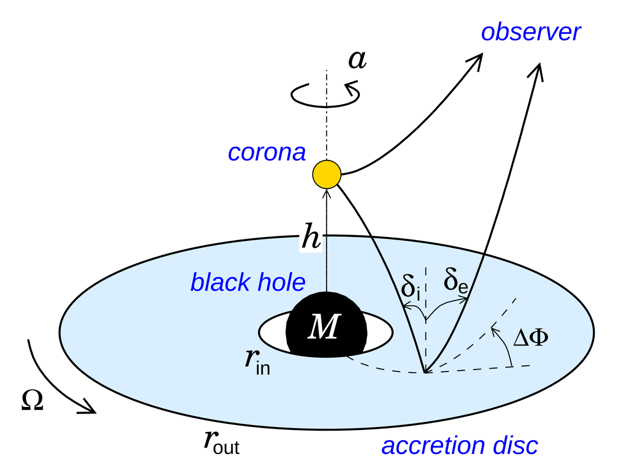
Black hole: Schwarzschild or maximally rotating Kerr metric for central gravitating body with the mass M and spin $a = 0$ or $a = 1$ in the dimensionless geometrical units $G = c = M = 1$ is used.

Accretion disc: co-rotating, Keplerian, geometrically thin, optically thick, cold disc extending from the marginally stable orbit $r_{\rm in} = r_{\rm ms}$ ($r_{\rm in} = 6$ or $r_{\rm in} = 1$) up to the upper edge at $r_{\rm out} = 1000$.

Corona: hot point-like patch of plasma located on the rotation axis at the height h above the centre and emitting isotropic power-law radiation $f = E^{-\Gamma}$ with the power-law index $\Gamma = 2$ for the specific photon number density flux.

Observer: sitting at infinity with the inclination angle $\theta_{\rm o}$.

Fig. 1: The sketch of the model



Methods and approximations

Light rays: Full relativistic ray-tracing code in vacuum is used for photon paths from the corona to the disc and from the disc to the observer.

Reflection: Monte Carlo multi-scattering computations for the cold disc are used for the reflected flux including the Fe fluorescent Kα and Kβ lines. Single scattering approximation is used for the local polarization of the reflected continuum component, the line flux and the primary radiation are supposed to be unpolarized. Both the reflected flux and the local polarization depend on the incident and emission angles $\delta_{\rm i}$, $\delta_{\rm e}$ and relative azimuthal angle $\Delta\Phi$ between incident and emitted light rays.

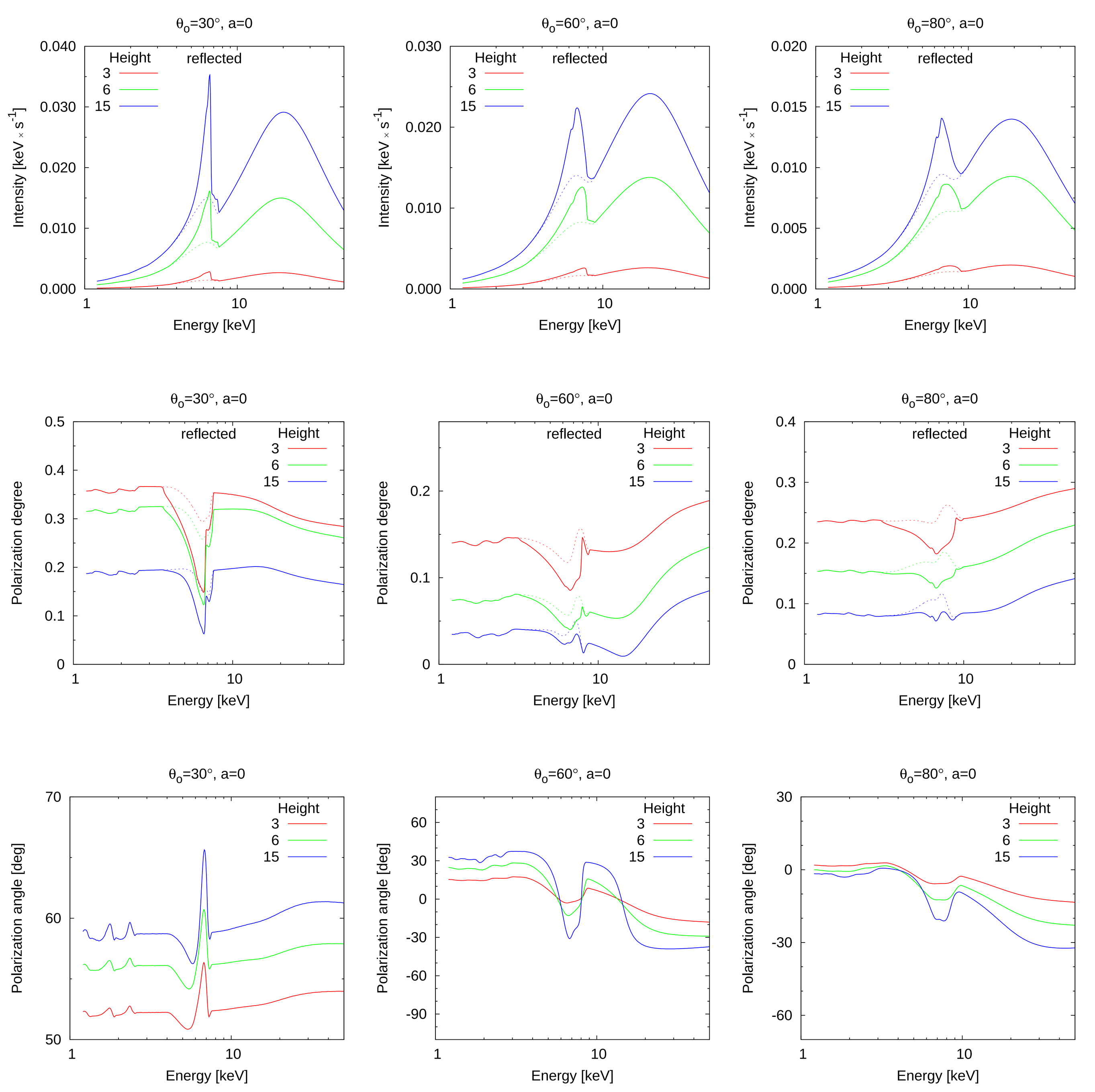


Fig. 2 $a = 0$, $r_{\rm in} = 6$ ⟵

Fig. 3 $a = 1$, $r_{\rm in} = 1$ ⟶

The reflected component

The energy dependence of the *intensity*, *polarization degree* and *polarization angle* (from top to bottom) of the reflected component as the observer at infinity would detect.

The observer *inclination* is $\theta_{\rm o} = 30°, 60°$ and $80°$ (from left to right).

The results for different *heights* $h = 3$, 6 and 15 are denoted by different *colours*.

The *solid* curves show the results with the relativistically broadened fluorescent iron Kα and Kβ spectral lines.

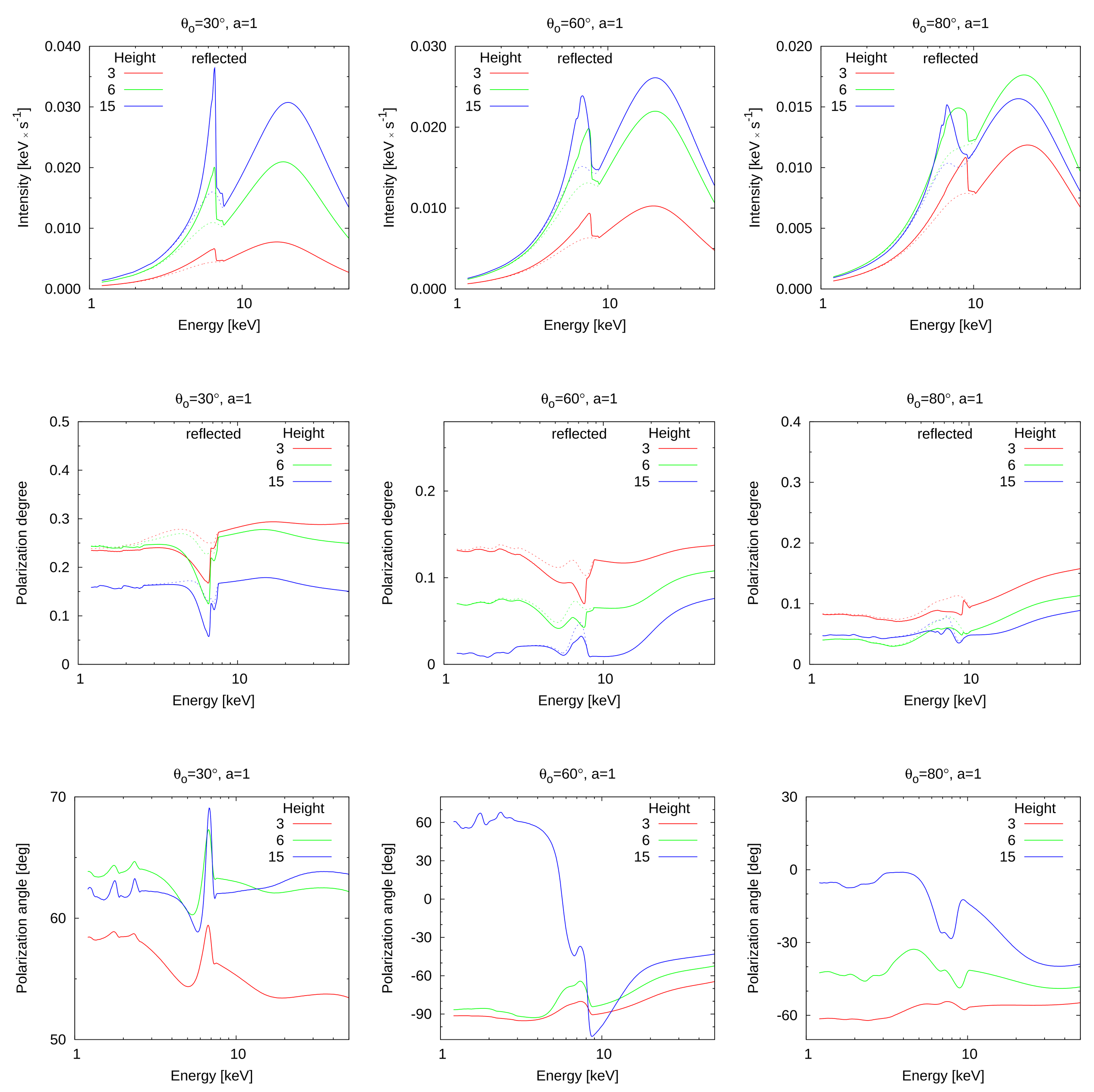
The *dotted* curves show the results for the continuum component only with the relativistically blurred iron absorption edge as the characteristic feature.

The *Fig. 2* on the left shows the results for the non-rotating Schwarzschild black hole with the spin $a = 0$ and the disc's inner edge at $r_{\rm in} = 6$.

The *Fig. 3* on the right shows the results for the highly spinning Kerr black hole with the spin $a = 1$ and the accretion disc extending down to the marginally stable orbit at $r_{\rm in} = 1$.

The polarization degree shown would be zero for unpolarized light and unity for totally polarized light.

Note that whereas the intensity and polarization degree would change with the primary flux taken into account, the polarization angle would stay the same.



Results

Intensity: The main features in the spectra between $2 - 10$ keV are well-known relativistic broad iron lines Kα and Kβ. These are broader for higher inclinations and for discs extending closer to the horizon. The Compton hump dominates at higher energy, it peaks around 20 keV. The flux scales with the observer inclination in most cases, however, the relativistic effects greatly amplify the reflected component of the flux for low heights of the primary source and disc extending closer to the black hole (i.e. for high spin).

Polarization degree: In our case, the fluorescent emission lines are intrinsically unpolarized and thus, they are responsible for the decrease in polarization degree (when comparing to the case with continuum only) in the energy range where they are shifted to by the relativistic effects.

If we disregard the spectral lines, the iron absorption edge manifests itself clearly either by the increase or decrease in the polarization degree. The polarization degree is higher for higher energy bands if we take into account the primary flux which exponentially decreases with the energy. Moreover the polarization of Compton hump increases it even further. Very interesting result is that for low heights of the primary illuminating source the polarization degree is higher for extremely spinning black hole ($a = 1$) when the accretion disc reaches closer to the black hole's horizon ($r_{\rm in} = r_{\rm ms} = 1$). Yet another interesting result is that the polarization degree has a maximum at low observer inclination. For the heights of the primary source around $h = 6$ its maximum is achieved close to **20°** when the observed intensity would be **16%** polarized in the energy range $20 - 50$ keV.

Polarization angle: The unpolarized iron lines do not have any effect on polarization angle, thus the iron absorption edge is the only feature that stands out in the polarization angle energy dependence. This effect can change the value of the polarization angle by quite a large amount. The polarization angle depends strongly on the spin of the black hole for systems with high inclination and low heights of the primary source. The rapid change in the dependence of the polarization angle on the inclination (see bottom middle panel in Fig. 4) is caused by the fact that the critical point, where the photons are emitted perpendicularly to the disc, moves from the well illuminated region of the disc either to the area below the marginally stable orbit in the case of the non-spinning black hole or to the region that is not illuminated so much in the case of the spinning black hole and higher heights of the primary source.

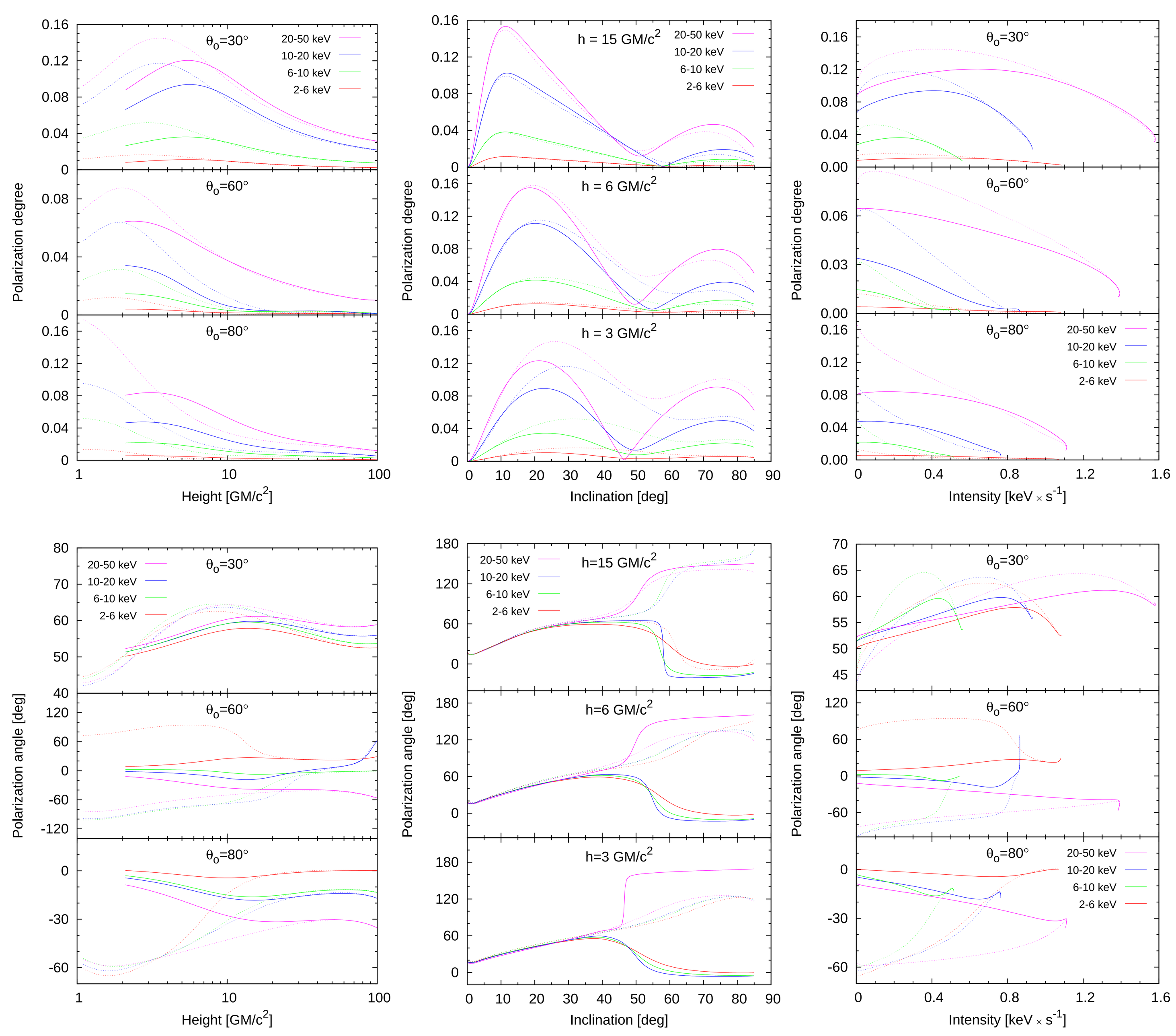


Fig. 4

The polarization at infinity

The dependence of the *polarization degree* (top panels) and *polarization angle* (bottom panels) on the height of the primary source (left), inclination (middle) and total intensity (right) as the observer at infinity would measure. Here, the radiation from the primary source is taken into account as well.

The observer *inclination* in the left and right panels is $\theta_{\rm o} = 30°, 60°$ and $80°$ (from top to bottom) and the *height* in the middle panels is $h = 3$, 6 and 15 (from bottom to top).

The results for different energy ranges $2 - 6$, $6 - 10$, $10 - 20$ and $20 - 50$ keV are denoted by different *colours*.

The graphs in *solid* lines show the results for the non-spinning Schwarzschild black hole ($a = 0$) while the *dotted* lines are for highly spinning Kerr black hole ($a = 1$).

The polarization degree shown would be zero for unpolarized light and unity for totally polarized light.

Conclusions

Lower polarization of broad Fe line region: This effect could be used to discriminate between the iron line models and partial covering models that are proposed to explain the excess of flux in the spectra of black-hole accretion discs between $2 - 10$ keV.

Properties of the system: Polarimetry is another important channel that can help us to uncover the physical parameters of the black-hole accretion disc systems such as *the black hole spin, the system inclination* and *the height of the illuminating source*.

Acknowledgments

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References

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